

Clinical Study

Abnormalities of the Ventilatory Equivalent for Carbon Dioxide in Patients with Chronic Heart Failure

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Received 21 December 2011; Accepted 9 February 2012

Academic Editor: Roland Wensel

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Introduction. The relation between minute ventilation (VE) and carbon dioxide production (VCO_2) can be characterised by the instantaneous ratio of ventilation to carbon dioxide production, the ventilatory equivalent for CO_2 (VEqCO_2). We hypothesised that the time taken to achieve the lowest VEqCO_2 (time to VEqCO_2 nadir) may be a prognostic marker in patients with chronic heart failure (CHF). **Methods.** Patients and healthy controls underwent a symptom-limited, cardiopulmonary exercise test (CPET) on a treadmill to volitional exhaustion. **Results.** 423 patients with CHF (mean age 63 ± 12 years; 80% males) and 78 healthy controls (62% males; age 61 ± 11 years) were recruited. Time to VEqCO_2 nadir was shorter in patients than controls (327 ± 204 s versus 514 ± 187 s; $P = 0.0001$). Univariable predictors of all-cause mortality included peak oxygen uptake ($X^2 = 53.0$), VEqCO_2 nadir ($X^2 = 47.9$), and time to VEqCO_2 nadir ($X^2 = 24.0$). In an adjusted Cox multivariable proportional hazards model, peak oxygen uptake ($X^2 = 16.7$) and VEqCO_2 nadir ($X^2 = 17.9$) were the most significant independent predictors of all-cause mortality. **Conclusion.** The time to VEqCO_2 nadir was shorter in patients with CHF than in normal subjects and was a predictor of subsequent mortality.

1. Introduction

Cardiopulmonary exercise testing (CPET) is used to stratify risk in patients with cardiorespiratory disease [1]. In patients with chronic heart failure (CHF), the normal linear relation between ventilation (VE) and carbon dioxide production (VCO_2) is maintained, but the slope of the relation is greater than normal, so that, for a given volume of carbon dioxide production, the ventilatory response is greater [2–6]. Another way of characterising the relation between minute ventilation and carbon dioxide production is the instantaneous ratio of ventilation to carbon dioxide production, the ventilatory equivalent for CO_2 (VEqCO_2). Recently, we have shown that the lowest VEqCO_2 (VEqCO_2 nadir) provides greater prognostic value than other CPET-derived variables in patients with suspected CHF [7]. Other studies have reported that the lowest VEqCO_2 has similar prognostic

power to the VE/VCO_2 slope derived from the whole of exercise [8].

During an incremental CPET, as exercise intensity increases, both VCO_2 and VE increase linearly. However, VEqCO_2 falls at the onset of exercise, possibly due to a reduction in dead space ventilation. Beyond the ventilatory compensation point (VCP), lactic acid production causes an increase in ventilation relative to carbon dioxide production, and thus the VEqCO_2 rises. Although patients with CHF have the same pattern of VEqCO_2 during exercise as normal subjects, with more severe heart failure, the increase in VEqCO_2 towards the end of exercise becomes more marked [9]. In the most severely affected patients, VEqCO_2 increases from the start of exercise [9]. We hypothesised that the time taken to reach VEqCO_2 nadir would be shorter in patients with CHF compared to healthy controls and thus may be an important prognostic indicator.

2. Methods

The Hull and East Riding Ethics Committee approved the study, and all patients provided informed consent. We recruited consecutive patients referred to a community heart failure clinic with symptoms of breathlessness (NYHA functional class II-III) who were found to have left ventricular systolic dysfunction on investigation. Clinical information obtained included past medical history and drug and smoking history. Clinical examination included assessment of body mass index (BMI), heart rate, rhythm, and blood pressure. Patients were excluded if they were unable to exercise because of noncardiac limitations (such as osteoarthritis) or had significant respiratory disease (defined as a predicted $FEV_1 < 70\%$).

Heart failure was defined as the presence of current symptoms of HF, or a history of symptoms controlled by ongoing therapy, and impaired left ventricular systolic function. Left ventricular function was determined from 2D echocardiography which was carried out by one of three trained operators. Left ventricular function was assessed by estimation on a scale of normal, mild, mild-to-moderate, moderate, moderate-to-severe, and severe impairment and was assessed by a second operator blind to the assessment of the first; where there was disagreement on the severity of left ventricular (LV) dysfunction, the echocardiogram was reviewed jointly with the third operator and a consensus reached. Where possible, left ventricular ejection fraction (LVEF) was calculated using the Simpson's formula from measurements of end-diastolic and end-systolic volumes on apical 2D views, following the guidelines of Schiller and colleagues [10], and LVSD was diagnosed if LVEF was $\leq 45\%$. When LVEF could not be calculated, LVSD was diagnosed if LVEF ≤ 45 or there was at least "mild-to-moderate" impairment.

Patients underwent a symptom-limited, maximal CPET on a treadmill using the Bruce protocol modified by the addition of a Stage 0 ($2.74 \text{ km} \cdot \text{h}^{-1}$ and 0% gradient) at the onset of exercise. Metabolic gas exchange was measured with an Oxycon Delta metabolic cart (VIASYS Healthcare Inc., Philadelphia, PA, USA). Peak oxygen uptake (pVO_2) was calculated as the average VO_2 for the final 30 s of exercise. The ventilatory anaerobic threshold (AT) was calculated by the V-slope method [11]. The gradient of the relationship between VE and VCO_2 (VE/ VCO_2 slope) was calculated by linear regression analysis using data acquired from the whole test. The VE/ QCO_2 relation was plotted from start to the finish of exercise. Each consecutive 30-second reading was averaged, and the lowest point was defined as the VE/ QCO_2 nadir [7]. The time taken to reach the VE/ QCO_2 nadir was reported in seconds (s). The peak respiratory exchange ratio ($pRER$) was calculated as the mean VCO_2/VO_2 ratio for the final 30 s of exercise. For comparative purposes, we also included a healthy control group who had no evidence of cardiac, respiratory, or musculoskeletal limitation. Healthy controls were randomly invited to participate from two local GP practices.

2.1. Statistical Analysis. We used SPSS (version 17.0) for statistical analysis. Continuous variables are presented as

mean \pm SD, and categorical data are presented as percentages. Continuous variables were assessed for normality by the Kolmogorov-Smirnov test. An arbitrary level of 5% statistical significance was used throughout (two tailed). An independent t -test was used to measure differences between CHF patients and healthy controls. All survivors were followed for a minimum of 12 months, and we therefore give the probability of 12-month survival. Receiver operator characteristic (ROC) curves were used to identify the value of the strongest predictor variables of survival to 12 months. We reported the area under the curve (AUC) with 95% confidence intervals (CI), sensitivity, specificity, and optimal cut-points in our ROC analysis. To define the optimal cut-point, we used the point closest to the upper left corner of the ROC curve, often known as the (0, 1) criterion.

All baseline variables (Table 1) were entered as potential univariable predictors of mortality using Cox analysis, and we adjusted for age, sex, BMI, aetiology of heart failure, and severity of LV dysfunction (none, trivial, mild, mild-to-moderate, moderate, moderate-to-severe, severe). Model building was based on backward elimination (P value for entry was < 0.05 ; P value for removal > 0.1). A multivariable Cox proportional hazards model using the backward likelihood ratio method was used to identify independent predictors of all-cause mortality from all significant candidate predictor variables. The outcome measure was all-cause mortality. Kaplan-Meier survival curves were plotted for the strongest candidate predictors; data were dichotomised by optimal cut-points.

3. Results

423 patients with CHF (mean age 63 ± 12 years; 80% males; LVEF $36 \pm 6\%$; peak VO_2 $22.3 \pm 8.1 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$; VE/ VCO_2 slope 34 ± 8) were included in the study. Of these, 75% were taking ACE inhibitors, 77% beta blockers, and 67% loop diuretics. Seventy eight healthy subjects (62% males; age 61 ± 11 years) were recruited as a control group. The healthy controls had a higher peak oxygen uptake, lower VE/ VCO_2 slope, and lower VE/ QCO_2 nadir (Table 1). Time to VE/ QCO_2 nadir was shorter in patients than controls (327 ± 204 s versus 514 ± 187 s; $P = 0.0001$) but was similar as a percentage of the total exercise duration in both groups ($55 \pm 23\%$ versus $60 \pm 17\%$; $P = 0.077$). We performed a subgroup analysis in 62 NYHA class III patients and found that the time to VE/ QCO_2 nadir was significantly lower (199 ± 59 s) compared to other less symptomatic patients (344 ± 202 s; $P < 0.0001$). We also performed a subgroup analysis by sex and found that the time to VE/ QCO_2 nadir was very similar between males (327 ± 209 s) and females (328 ± 94 s; $P > 0.05$; $n = 85$).

In patients, time to VE/ QCO_2 nadir correlated with age ($r = -0.17$; $P = 0.0001$) and LVEF ($r = 0.24$; $P = 0.0001$) but was not associated with BMI ($r = 0.001$; $P = 0.98$). Time to VE/ QCO_2 nadir correlated with peak oxygen uptake ($r = 0.59$; $P = 0.001$) and showed an inverse association with both VE/ VCO_2 slope ($r = -0.55$; $P = 0.001$) and VE/ QCO_2 nadir ($r = -0.56$; $P = 0.001$). Scatter plots showing the association between time to VE/ QCO_2 nadir, peak oxygen uptake, and

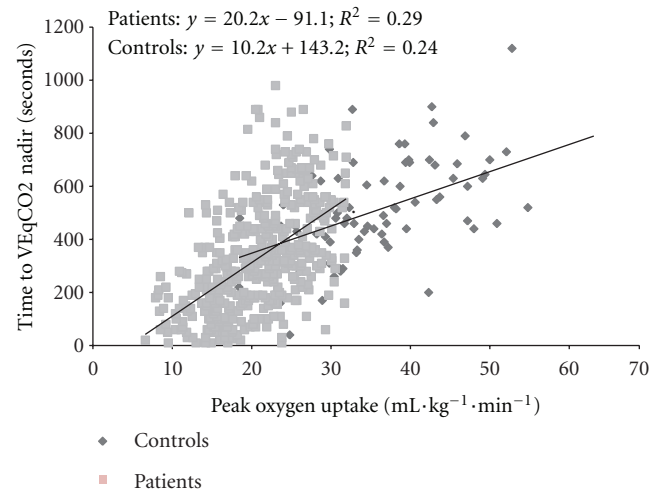
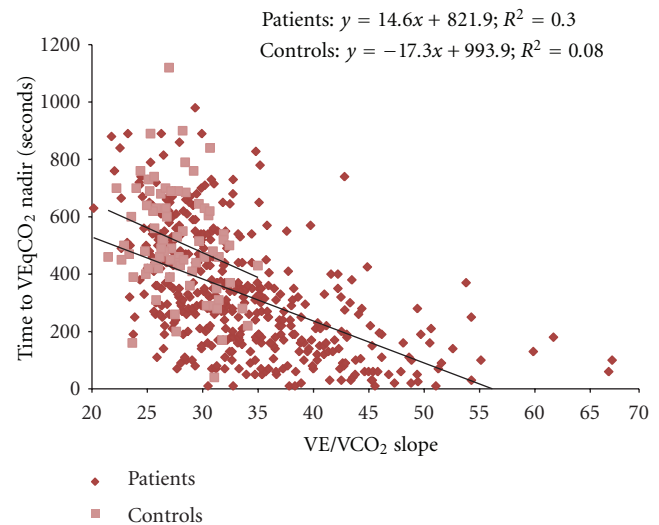
TABLE 1: Baseline clinical characteristics between CHF patients and healthy controls.

Variable (mean \pm SD)	CHF patients	Healthy controls	P value*
N	423	78	—
Males (%)	80	62	0.0001*
Age (years)	63 (12)	61 (11)	0.529
BMI ($\text{kg}\cdot\text{m}^{-2}$)	28 (5)	26 (3)	0.001*
LVEF (%)	36 (6)	60 (6)	0.0001*
pVO ₂ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	22.3 (8.1)	36.2 (8.8)	0.0001*
VE/VCO ₂ slope (full)	33.8 (7.7)	27.7 (3.0)	0.0001*
VEqCO ₂ nadir	32.4 (6.2)	26.5 (3.0)	0.0001*
Time to VEqCO ₂ nadir(s)	327 (514)	514 (187)	0.0001*
AT ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	15.2 (5.7)	23.4 (6.6)	0.0001*
Peak RER	1.07 (0.10)	1.08 (0.06)	0.223
Exercise duration (s)	564 (250)	881 (256)	0.0001*
Heart rate (rest) (beats $\cdot\text{min}^{-1}$)	76 (15)	72 (12)	0.079
Heart rate (peak) (beats $\cdot\text{min}^{-1}$)	136 (30)	165 (20)	0.0001*
Systolic BP (rest) (mmHg)	137 (25)	148 (20)	0.0001*
Systolic BP (peak) (mmHg)	172 (36)	199 (22)	0.0001*
Diastolic BP (rest) (mmHg)	84 (15)	90 (9)	0.0001*
Diastolic BP (peak) (mmHg)	93 (22)	101 (21)	0.003*
Loop diuretic (%)	67	—	—
ACE-I (%)	75	—	—
Beta-blocker (%)	77	—	—

BMI: body mass index; LVEF: left ventricular ejection fraction; pVO₂: peak oxygen uptake; ACE-I: ACE inhibitor; peak RER: peak respiratory exchange ratio; AT: anaerobic threshold; BP: blood pressure; *differences between CHF and healthy controls, $P < 0.05$.

VE/VCO₂ slope in patients and controls are shown in Figures 1 and 2.

One hundred and eighteen patients (28%) died during followup. The median followup in survivors was 8.6 ± 2.1 years. Univariable predictors of outcome derived from CPET are shown in Table 2. With the exception of resting heart rate, all candidate variables were significant univariable predictors. The strongest univariable predictors of all-cause mortality were peak oxygen uptake ($\chi^2 = 53.0$), VEqCO₂ nadir ($\chi^2 = 47.9$), VE/VCO₂ slope ($\chi^2 = 31.7$), and time to VEqCO₂ nadir ($\chi^2 = 24.0$). In a Cox multivariable proportional hazards model adjusted for age, sex, BMI, and severity of LV dysfunction, peak oxygen uptake ($\chi^2 = 16.7$; HR = 0.91; 95% CI 0.88–0.95; $P = 0.0001$) and VEqCO₂ nadir ($\chi^2 = 17.9$; HR = 1.12; 95% CI 1.04–1.20; $P = 0.0001$) were the most significant independent predictors of mortality.

FIGURE 1: Relation between time to VEqCO₂ nadir and peak oxygen uptake in patients with CHF and controls.FIGURE 2: Relation between time to VEqCO₂ nadir and VE/VCO₂ slope in patients with CHF and controls.

ROC curve analysis of the relation between time to VEqCO₂ nadir (and both VEqCO₂ nadir and peak VO₂) and all-cause mortality at 12 months is shown in Figure 3. Time to VEqCO₂ nadir (AUC = 0.75; $P < 0.0001$; 95% CI = 0.67–0.84; sensitivity = 81; specificity = 62; optimal cut-point = 250 s); VEqCO₂ nadir (AUC = 0.81; $P < 0.0001$; 95% CI = 0.74–0.89; sensitivity = 86; specificity = 62; optimal cut-point = 33); peak VO₂ (AUC = 0.76; $P < 0.0001$; 95% CI = 0.67–0.85; sensitivity = 86; specificity = 57; optimal cut-point = 20 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were similar in their relation to all-cause mortality at 12 months. Optimal cut-points determined from ROC analysis were used to construct Kaplan-Meier survival curves for time to VEqCO₂ nadir (Figure 4), VEqCO₂ nadir (Figure 5), and peak VO₂ (Figure 6).

TABLE 2: Unadjusted univariable predictors of outcome (in order of Chi-square value).

Variables	P value	HR	95% CI	Chi-square
Peak oxygen uptake	0.0001	0.891	0.862	53.0
VEqCO ₂ nadir	0.0001	1.095	1.068	47.9
VE/VCO ₂ slope	0.0001	1.060	1.041	31.7
Time to VEqCO ₂ nadir*	0.0001	0.705	0.523	24.0
Heart rate at peak exercise	0.0001	0.995	0.978	18.5
Systolic blood pressure (rest)	0.001	0.986	0.978	12.0
Diastolic blood pressure (rest)	0.02	0.977	0.963	9.3
Heart rate (rest)	0.744	1.002	0.990	0.1

HR: hazard ratio; 95% CI: 95% confidence intervals; *adjusted HR associated with 10 s increase in time to VEqCO₂ nadir.

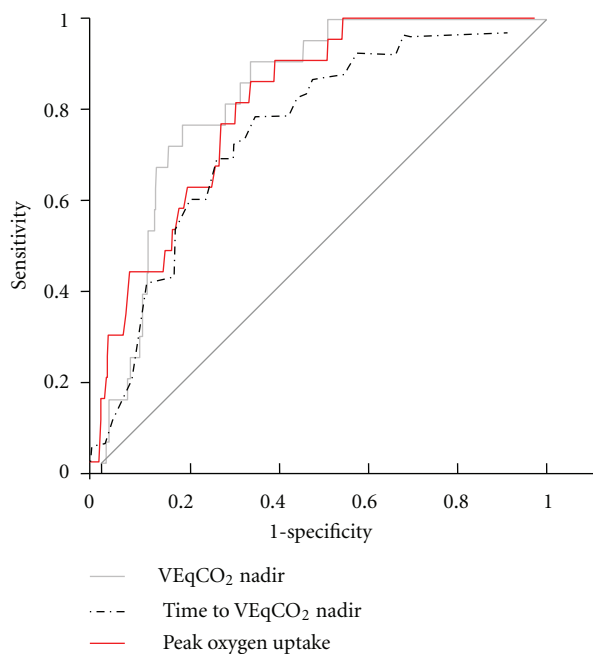


FIGURE 3: Receiver operating characteristic curve showing value of VEqCO₂ nadir, time to VEqCO₂ nadir, and peak oxygen uptake for predicting all-cause mortality at 12 months. VEqCO₂ nadir: AUC = 0.81; $P < 0.0001$; 95% CI = 0.74–0.89; sensitivity = 86; specificity = 62; optimal cut-point = 33; time to VEqCO₂ nadir: AUC = 0.75; $P < 0.0001$; 95% CI = 0.67–0.84; sensitivity = 81; specificity = 62; optimal cut-point = 250 s; peak VO₂: AUC = 0.76; $P < 0.0001$; 95% CI = 0.67–0.85; sensitivity = 86; specificity = 57; optimal cut-point = 20 mL·kg⁻¹·min⁻¹.

4. Discussion

We have shown that the time to VEqCO₂ nadir is significantly lower in patients with CHF compared to controls. To our knowledge, no previous study has evaluated the prognostic value of time to VEqCO₂ nadir. Sun and colleagues [12] showed that the lowest VEqCO₂ (VEqCO₂ nadir) was the most stable marker of ventilatory inefficiency in healthy controls. During maximal exercise testing, the VEqCO₂ nadir was achieved at around the ventilatory anaerobic threshold and occurred during “moderate” exercise intensity. Both VE and VCO₂ are linearly related up to the ventilatory

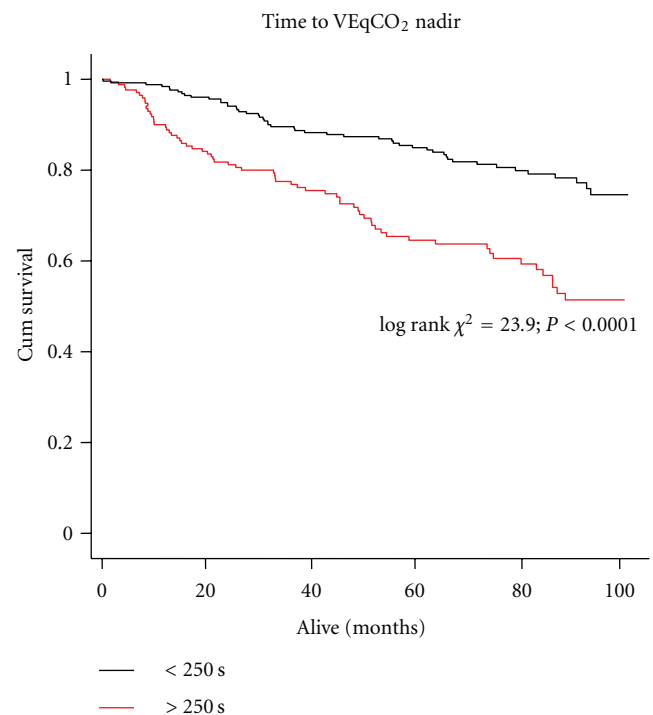


FIGURE 4: Kaplan-Meier survival curve showing time to VEqCO₂ nadir-data dichotomised by optimal cut-points (<250 s; $n = 170$, event free survival 61%; ≥ 250 s $n = 254$ patients, event free survival 80%).

compensation point (VCP). Beyond this point (during heavy to maximal exertion), an increase in VE relative to VCO₂ is dependent upon the fall in pH and PaCO₂ [12].

The exaggerated ventilatory response of patients with CHF is seen at the outset of exercise; that is, the VE/VCO₂ slope is abnormal from the moment exercise starts. A wide variety of factors has been proposed as the reason for the increase in VE/VCO₂ slope including an increased dead space and resultant “wasted” ventilation [13–15], early metabolic acidosis [16], and overactivation of chemoreceptors and ergoreceptors [17, 18]. The fall in the VEqCO₂ at the onset of exercise is at least in part due to the reduction in fixed anatomical dead space ventilation as a proportion of total ventilation at the onset of exercise, but the increase after

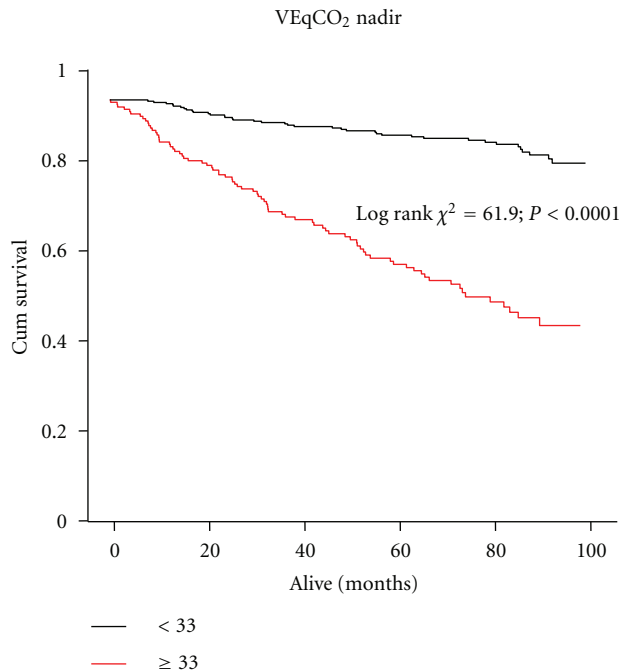


FIGURE 5: Kaplan-Meier survival curve showing VEqCO₂ nadir-data dichotomised by optimal cut-points (<33 *n* = 252 patients, event free survival 85%; ≥33 *n* = 171 patients, event free survival 54%).

the plateau phase is due to a non-CO₂ stimulus to ventilation, whether lactate production or an alternative stimulus to ventilation, such as the ergoreflex [9, 19]. The shorter time to VEqCO₂ nadir reflects the earlier onset (and more important influence of) the non-CO₂ stimulus to ventilation in patients with CHF.

We found a strong relation between the time to VEqCO₂ nadir and mortality. The time to VEqCO₂ nadir was an important univariable predictor of all-cause mortality although it was outperformed by peak oxygen uptake and VEqCO₂ nadir in a multivariable survival model. We have previously shown that peak oxygen uptake [20] and VEqCO₂ nadir [7] are independent predictors of all-cause mortality in patients with CHF. Other investigators have also reported similar findings [8, 21].

A limitation of our study is that we do not have test-retest CPET data for individual patients/controls; therefore, we cannot determine the reproducibility of the time to VEqCO₂ nadir in either healthy or diseased populations.

Cardiopulmonary exercise testing provides two broad types of prognostic variable: a measure of exercise capacity, such as peak VO₂, reflecting the complex relation between pump, ventilator, and muscle extraction; and a measure of the ventilatory response to exercise, such as the VE/VCO₂ slope or time to VEqCO₂ nadir, reflecting the abnormal stimulus to ventilation in CHF. The time to VEqCO₂ nadir following maximal CPET was shorter in patients with CHF than in normal subjects and is a predictor of subsequent mortality.

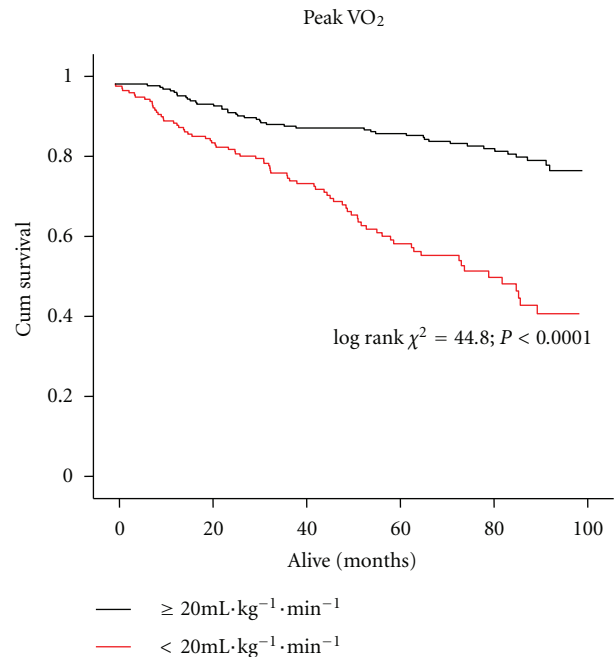


FIGURE 6: Kaplan-Meier survival curve showing peak VO₂-data dichotomised by optimal cut-points (<20 mL·kg⁻¹·min⁻¹ *n* = 184 patients, event free survival 60%; ≥ 20 mL·kg⁻¹·min⁻¹ *n* = 239 patients, event free survival 82%).

5. Clinical Messages

- (i) Cardiopulmonary exercise testing is becoming increasingly important for prescribing appropriate exercise training volumes in patients with cardiovascular disease including CHF.
- (ii) The ventilatory response to exercise is abnormal in patients with CHF compared to age-matched controls.
- (iii) Metabolic responses to exercise are important predictors of risk and should be monitored prior to and following a program of rehabilitation in patients with CHF.

Conflict of interests

The authors declare that there is no conflict of interests.

Acknowledgment

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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